Remote Sensing and Modeling of Wildfires

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***Abstract*—The application of satellite remote sensing to the detection and study of wildfires has grown rapidly in recent years as new tools have become available and are put into use. Space borne imagery can provide a unique perspective to viewing the fire giving space/time coverage not available with any other observational system. One aspect of fires that can both be detected with satellite imagery and modeled numerically is the smoke plume produced by the fire. Surprisingly, most models designed to study smoke plumes were created to study controlled burns and not wildfires. We use one such model to compare model simulations with a suite of different types of satellite imagery to study a major wildfire. The 2003 Aspen Fire in the mountains north of Tucson, Arizona is used as a case study for the analysis of satellite imagery of a wildfire smoke plume in conjunction with model simulations of this plume. We clearly demonstrate that this plume model can be used to adequately simulate the fire plume as depicted in the satellite imagery when the plume achieves a sufficient altitude. For weak fires and low wind conditions the plumes often follow the local surface topography.**

***Index Terms*—AVHRR, fires, plume models, QuickBird**

I. Introduction

The Aspen Fire burned from 17 June to 11 July, 2003 in the Santa Catalina Mountains just north of Tucson, Arizona. We will use this fire in a case study to understand how satellite remote sensing can be used together with numerical model simulations to map and monitor the behavior of the smoke plumes associated with this fire. This case study demonstrates how developing technologies in satellite remote sensing make it possible for fire related products such as plume mapping to be applied to fire detection and the real time monitoring of wildfires. This will be enhanced by high performance computing tools such as artificial neural network algorithms [1], [2].

Satellite imagery can possibly provide useful input for firefighters particularly when coupled with numerical simulations that can also be used in a predictive sense. In our study we will use a model developed to simulate the smoke plumes of controlled burns to compare with different satellite images of the Aspen Fire near Tucson. Surprisingly this and most other models have not been developed for wildfires but rather only for controlled burns. Few comparisons of observations of plume behavior from actual wildfires to models currently exist [3], [4]. Only a small number of studies have focused on smoke plume identification in satellite imagery because the overlap of spectral signatures between smoke, clouds and highly reflective surfaces creates difficulties in isolating the smoke signature [5].

We use the National Forest Service Lagrangian puff dispersion model (NFSPUFF) in conjunction with satellite imagery from two different satellite sensors to study the space/time variability of the Aspen Fire smoke plumes. This comparison clearly demonstrates the ability of the model to simulate the downwind distribution and dispersion of the smoke plumes as seen in the satellite imagery. Thus, the model becomes a tool for monitoring and forecasting the behavior of the fire.

II. Remote Sensing Data Sets

DigitalGlobe's QuickBird and the National Oceanic and Atmospheric Administration's (NOAA) Advanced Very High Resolution Radiometer (AVHRR) are used together to study the evolution of the smoke plume associated with the Aspen Fire. We also use the space/time characterization of the fire plume available with these satellite data to verify the simulations of the fire plume by the NFSPUFF smoke plume dispersion model. The high-resolution capability of the QuickBird imagery can be used to accurately locate the fire source while the lower spatial resolution AVHRR imagery can be used to monitor the time series evolution of the smoke plume.

The QuickBird satellite sensor has four multispectral bands with a 2.8 m spatial resolution at 450-520 nm, 520-600 nm, 630-690 nm, and 760-900 nm covering the blue, green, red and near-infrared (NIR) bands respectively. The AVHRR-2 that collected the data available for this fire event had 5 spectral bands with a 1 km horizontal spatial resolution at 580-680 nm, 725-1100 nm, 3550-3930 nm, 10300-11300 nm and 11500-12500 nm for red, NIR, mid-wave infrared (MIR) and two thermal infrared (TIR) bands. The TIR bands are emitted thermal radiances while the first two bands are reflectance values. The mid-wave infrared contains both reflected and emitted radiation.

Historically, the Normalized Difference Vegetation Index (NDVI) has been used to indicate the health of vegetation. This vegetation index has well-known deficiencies in vegetation detection and mapping linked to atmospheric influences and soil background influences. Nevertheless, it is still a useful tool for fire plume detection and mapping [6]. This particular use of the NDVI is based on the difference in

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reflectance between band 1 (the visible) and the NIR in channel 2 in the AVHRR. Atmospheric aerosols increase the apparent reflectance in the visible (centered on the red) band and to a lesser extent decreases the reflectance in the NIR band [7].

To generate an image in which the smoke plume is clearly evident the data is first radiometrically calibrated to reflectance values for the visible bands and then geometrically corrected so that comparison between sensors and location of fire areas is made easier. The NDVI is calculated from the AVHRR as

$$\mathrm{NDVI} = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$$

A thresholding technique is often used with AVHRR data [1], [2], [8]. A ratio test of band 1 and band 2 is first used to identify smoke and distinguish them from cloud pixels. Fire pixels can be separated from highly reflective ground pixels by using brightness temperatures from AVHRR band 4, the 11 μm thermal infrared. It was found that the most effective threshold for the AVHRR imagery of the Aspen Fire was to identify pixels with a band 2 to band 1 ratio between 0.77 and 1.00 with a concurrent band 4 brightness temperature less than 317 K. The high spatial resolution of the QuickBird imagery can be used to validate the threshold algorithm used to locate regions of smoke in the AVHRR imagery.

The obvious advantage to the QuickBird imagery is their high spatial resolution which makes it possible to discern specific mountain features and to select the individual fire source sites that are generating the smoke plumes used later in the model simulations. The AVHRR imagery, with its lower spatial resolution, makes it more difficult to identify specific fire sites for model input but its frequent temporal coverage (many images per day of each area) makes it possible to monitoring the daily evolution of the fire plume and the relation of this plume evolution to changes in wind forcing of the numerical model.

III. The Model

As mentioned earlier the model used in this paper is a numerical model called NFSPUFF that has been used as a controlled burn plume prediction tool by the U.S. National Forest Service for many years. This model implements wildfire emissions, current and 42 hour forecast winds, a semi-empirical plume-rise model and a GIS data base for land surface topography. The model output includes plume trajectories for up to 16 simultaneous fire sites and can also be used to predict maximum PM concentrations at each puff and 24-hour average PM concentrations at the surface. This model has been compared to observations of fires with typical flame powers of 0.1 – 10 Giga Watts with reported plume-top errors of 300 m [9].

Although NFSPUFF was initially intended to be coupled with the Pennsylvania State University – National center for Atmospheric Research (PSU-NCAR) fifth-generation Mesoscale Meteorology Model (MM5) but due to time and computational constraints we decided to use model re-analyses from the National Center for Environmental Prediction (NCEP) for the necessary wind profiles to run the NFSPUFF model. These data were provided by the NOAA-Cooperative Institute for Research in Environmental Society (CIRES) Climate Diagnostic Center (CDC) through their website at http://www.cdc.noaa.gov/. The reanalysis data is gridded at a 2.5° latitude-longitude resolution and given four times daily at 00:00, 6:00, 12:00 and 18:00 UTC. The model requires wind inputs as 48-hour gridded east-west and north-south wind vectors at five separate pressure levels starting at 12:00 UTC. The NCEP analyses are interpolated to fit these requirements. The model start time is set at 16:00 UTC allowing time for the model to better simulate the actual fire conditions at 18:00 UTC which is the overpass time for the satellite imagery.

We found that by adjusting the burn acreage of the burn site in NFSPUFF the intensity of the fire is indirectly adjusted. Based on the satellite imagery combined with post-event knowledge of the fire itself, the burn site areas were set at 100 acres from 17 June through 30 June. Obviously more than that will burn in a given day. Based on the QuickBird imagery, however, hotspots that produced the most intense smoke were isolated to small areas. Between 1 and 2, July the fire died down and a 15 acre burn site was found to be appropriate. The fire flared up between 3 and 5 July, which required readjusting the burn sites back to 100 acres.

IV. The Aspen Fire

The Aspen Fire started on Sunday, 17 June, 2003 near the Aspen Trail on Marshall Peak in the Mount Lemmon Recreational Area atop the Santa Catalina Mountain Range. It had a significant impact on the local surroundings and considerable effort was required to bring the fire under control and to extinguish it. A total of 84,750 acres of forested region were burned and 340 structures destroyed by this wildfire including major structures in the town of Summerhaven, Arizona. The cost to fight this fire was totaled at $17 million [10].

A QuickBird false color image (Fig. 1) for 21 June, 2003 shows a well-developed wildfire with several hotspots, which mark the locations of the plume sources. In a later QuickBird image from 1 July, 2003 (Fig. 2) the smoke plumes are low and close to the ground as compared with the plumes in Fig. 1. Thus, the July plumes are not affected by the upper level winds as confirmed by the lack of shadows in the satellite image.

On 21 June strong fires were sustained by strong southwest winds and the model runs for this date compare very well with the plumes inferred using a threshold selection from the AVHRR image as shown in Fig. 3. As the plumes from the intense fire spots rise they are influenced by the mid-level winds, which turn the smoke towards the east. Based on the

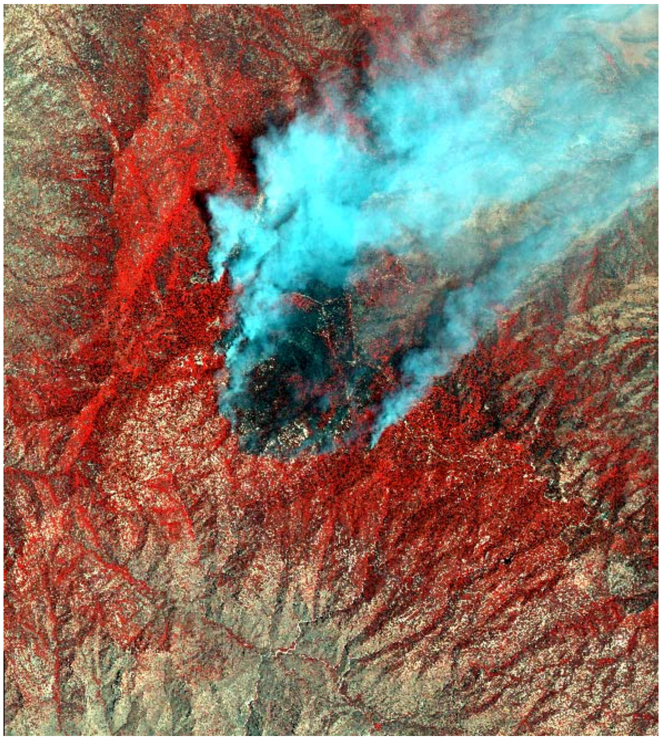

Figure 1. QuickBird false color imagery for 21 June 2003 at 18:00 UTC shows several hot spots within the Aspen Fire.

NCEP reanalysis data, the wind strengthens significantly at 2,500 m above the ground. This height influence is demonstrated in Fig. 4 which shows that the plume reaches 2,500 m by looking at the plume vertically at the side.

Smoke emitted by a fire is slightly warmer than the surrounding environment and will rise, expand and cool until it reaches an equilibrium height where the smoke has the same temperature as the surroundings. At this altitude the smoke plumes will be carried horizontally with the winds. In intense

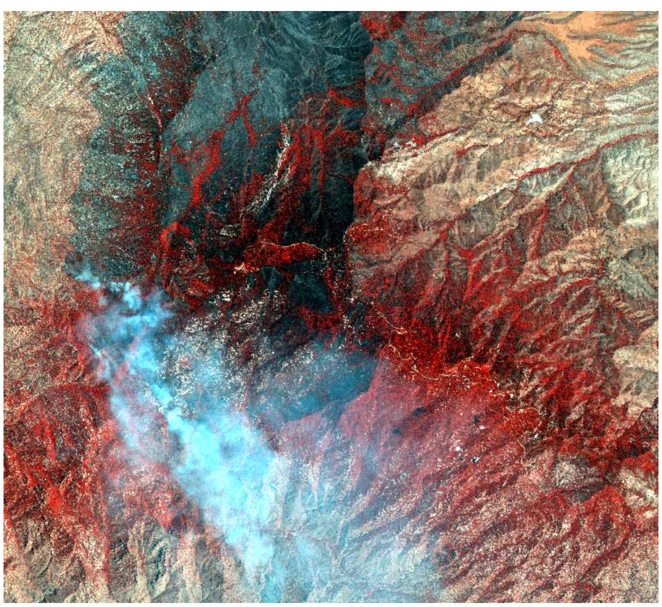

Figure 2. QuickBird false-color imagery for 1 July 2003 at 18:00 UTC shows a very disperse and low level smoke plume moving towards the southeast.

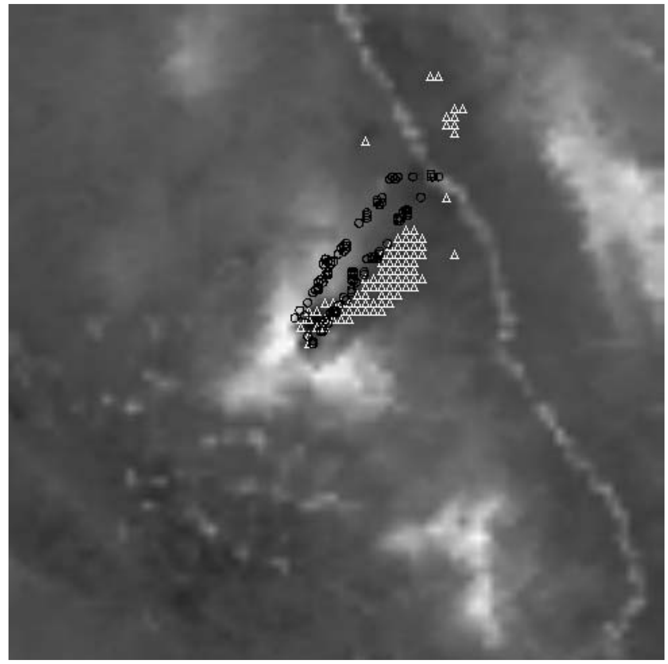

Figure 3. AVHRR NDVI imagery and model output is compared for 21 June 2003. In this NDVI image areas with vegetation appear lighter, while rocky, desert regions appear darker. The white line stretching from the top to the bottom of the image is where a well traveled dirt road runs along the San Pedro River. The smoke plume shows up as a black region in the imagery. The plume found by using the thresholding technique on the AVHRR data is represented by white triangles while the model output is in black circles.

fires, the generated smoke is warm enough to allow deep penetration into the atmosphere, while a less intense smoldering fire will be less hot and the associated plumes will not rise as high as others.

When little or no winds are present at the location of the hotspot generating the fire plumes and the fire at the hotspots is not intense, the smoke will collect at the surface and follow the surface topography under the influence of the local winds. The NFSPUFF model drainage winds under such conditions indeed tend to follow along the terrain in the absence of strong winds. It is common for winds to follow the topography in mountain regions and flow upslope in the afternoon and down slope in the evening [11]. In addition, it should be noted that the fire can also interact with and change the surrounding winds often making it difficult to predict what may happen with the smoke dynamics. The amount that a fire feeds-back on itself by affecting the surrounding atmosphere is contingent upon its intensity and the ambient atmospheric conditions. Low winds (< 5 ms^{-1}) and low fire intensity combined with the right surface topography make it very difficult to predict the location and path of the fire related smoke plumes.

The Aspen Fire has weakened and is almost under control by 1 July, so on this date the fire was reduced to a 15 acre fire in the NFSPUFF model instead of the 100 acre fire used in the initial simulation. However, modeling the Aspen Fire in a low wind environment and along with low, highly-dispersive smoke plumes made it very difficult to get a good agreement between the model and satellite expressions of the plumes.

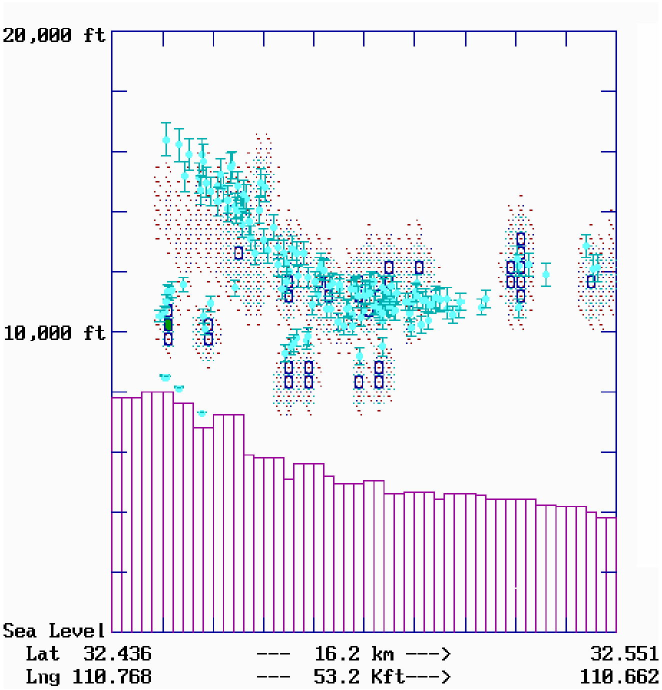

Figure 4. A model output cross-section for 21 June 2003 shows the plume reaches a height of approximately 16,000 ft above sea level (2,500 m above ground level).

These results suggest that unless the plumes can achieve a measurable altitude the NFSPUFF model cannot be relied on to give a good simulation of the smoke plume behavior.

In the QuickBird imagery from 1 July, 2003 the smoke is seen to move gradually towards the southeast. The fire at this time can be assumed to be fairly weak generating dispersive plumes that are relatively low. This low level is confirmed by the fact that the plume direction does not follow the known winds. Even though weak the winds were still about 5 ms^{-1} from the southwest, which should have driven the smoke plumes to the northeast. The fact that the plumes are instead directed towards the southeast is a result of the local topographic influence on these low smoke plumes, which channel the smoke plumes in this direction.

V. Conclusions

The Lagrangian NFSPUFF model was able to simulate the Aspen Fire smoke plumes as observed in two types of satellite imagery when the fire was strong enough that the plumes would achieve a relatively high altitude where strong winds cause the advection and dispersal of the plumes. Thus, this model can be used to simulate fire and smoke plume behavior in the early and strong stages of the fire and to predict fire behavior for up to 24-hours if near real-time wind profiles are available. As the fire intensity dies down and under low-wind conditions the model simulations became less accurate in predicting or simulating plume behavior and local surface topography plays an increasingly important role in the direction of plume movement and dispersion. The model is found to be most sensitive to the atmospheric wind profile that is used as input to the model while surface topography is important at the lower fire and wind intensity levels.

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